XI. *Experimental Researches in Electricity.—Twenty-ninth Series.* *By* MICHAEL FARADAY, *Esq., D.C.L., F.R.S., Fullerian Prof. Chem. Royal Institution, Foreign Associate of the Acad. Sciences, Paris, Ord. Boruss. Pour le Mérite, Eq., Memb. Royal and Imp. Acadd. of Sciences, Petersburgh, Florence, Copenhagen, Berlin, Göttingen, Modena, Stockholm, Munich, Bruxelles, Vienna, Bologna, &c. &c.*

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§ 35. *On the employment of the Induced Magneto-electric Current as a test and measure of Magnetic Forces.*

3177. THE proposition which I have made to use the induced magneto-electric current as an experimental indication of the presence, direction and amount of magnetic forces (3074.), makes it requisite that I should also clearly demonstrate the principles and develope the practice necessary for such a purpose; and especially that I should prove that the amount of current induced is precisely proportionate to the amount of lines of magnetic force intersected by the moving wire, in which the electric current is generated and appears (3082, 3109.). The proof already given is, I think, sufficient for those who may repeat the experiments; but in order to accumulate evidence, as is indeed but proper in the first announcement of such a proposition, I proceeded to experiment with the magnetic power of the earth, which presents us with a field of action, not rapidly varying in force with the distance, as in the case of small magnets, but one which for a given place may be considered as uniform in power and direction; for if a room be cleared of all common magnets, then the terrestrial lines of magnetic force which pass through it, have one common direction, being that of the dip, as indicated by a free needle or other means, and are in every part in equal proportion or quantity, *i.e.* have equal power. Now the force being the same everywhere, the proportion of it to the current evolved in the moving wire is then perhaps more simply and directly determined, than in the case where, a small magnet being employed, the force rapidly changes in amount with the distance.

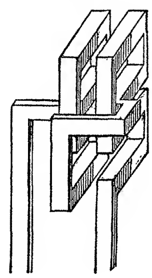
¶ i. *Galvanometer.*

3178. For such experimental results as I now propose to give, I must refer to the galvanometer employed and the precautions requisite for its proper use. The instrument has been already described in principle (3123.), and a figure of the conductor which surrounds the needles, given. This conductor may be considered as a square copper bar, 0·2 of an inch in thickness, which passes twice round the plane of vibration of each of the needles forming the astatic combination, and then is continued outwards and terminates in two descending portions, which are intended to dip into

cups of mercury. As both the needles are within the convolutions of this bar, an indicating bristle or fine wire of copper is fixed parallel to, and above them upon the same axis, and this, in travelling over the usual graduated circle, shows the place and the extent of vibration or swing of the needles below. The suspension is by cocoon silk, and in other respects the instrument is like a good ordinary galvanometer.

3179. It is highly important that the bar of copper about the needles should be perfectly clean. The vertical zero plane should, according to the construction, be midway between the two vertical coils of the bar, fig. 1; instead of which the needle at first pointed to the one side or the other, being evidently attracted by the upright portions of the bar. I at first feared that the copper was magnetic, but on cleaning the surface carefully with fine sand-paper, I was able to remove this effect, due no doubt to iron communicated by handling or the use of tools, and the needle then stood truly in a plane equidistant from the two coils, when that plane corresponded with the magnetic meridian.

Fig. 1.



3180. The connexions for this galvanometer (3123, 3133.) were all of copper rod or wire 0·2 of an inch in diameter; but even with wires of this thickness the extent of the conductors should not be made more than is necessary; for the increase from 6 to 8, 10 or 12 feet in length, makes a considerable difference at the galvanometer, when electric currents, low in intensity, are to be measured. It is most beautiful to observe in such cases the application of Ohm's law of currents to the effects produced. When the connexions were extended to a distance, straight lengths of wire with dropping ends were provided, and these by dipping into cups of mercury completed the connexion and circuit. The cups consisted of cavities turned in flat pieces of wood. The ends of the connecting rods and of the galvanometer bar were first tinned, and then amalgamated; after which their contact with the mercury was both ready and certain. Even where connexion had to be made by contact of the solid substances, I found it very convenient and certain to tin and amalgamate the ends of the conductors, wiping off the excess of mercury. The surfaces thus prepared are always ready for a good and perfect contact.

3181. When the needle has taken up its position under the earth's influence, and the copper coil is adjusted to it, the needle ought to stand at true zero, and appears so to do. When that is really the case, equal forces applied in succession on opposite sides of the needle (by two contrary currents through the coil for instance) ought to deflect the needle *equally* on both sides, and they do so. But sometimes, when the needle appears to stand at zero, it may not be truly in the magnetic meridian; for a little torsion in the suspension thread, even though it be only 10° or 15° (for an indifferent needle), and quite insensible to the eye looking at the magnetic needle, does deflect it, and then the force which opposes the swing of the needle, and which stops and returns the needle towards zero (being due both to the torsion and the earth's force), is not equal on the two sides, and the consequence is, that the extent of

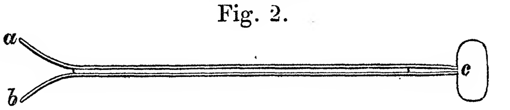
swing in the two directions is not equal for equal powers, but is greater on one side than the other.

3182. I have not yet seen a galvanometer which has an adjustment for the torsion of the suspending filament. Also, there may be other causes, as the presence about a room, in its walls and other places, of unknown masses of iron, which may render the forces on opposite sides of the instrument zero unequal in a slight degree; for these reasons it is better to make *double observations*. All the phenomena we have to deal with, present effects in two contrary directions. If a loop pass over the pole of a magnet (3133.), it produces a swing in one direction; if it be taken away, the swing is in the other direction; if the rectangles and rings to be described (3192.) be rotated one way, they produce one current; if the contrary way, the other and contrary current is produced. I have therefore always in measuring the power of a pole or the effect of a revolving intersecting wire made many observations in both directions, either alternately or irregularly; have then ascertained the average of those on the one side, and also on the other (which have differed in different cases from $\frac{1}{50}$th to $\frac{1}{300}$th part), and have then taken the mean of these averages as the expression of the power of the induced electric current, or of the magnetic forces inducing it.

3183. Care must be taken as to the position of the instrument and apparatus connected with it, in relation to a fire or sources of different temperatures, that parts which can generate thermo-currents may not become warmed or cooled in different degrees. The instrument is exceedingly sensible to thermo-electric currents; the accidental falling of a sun-beam upon one of two connecting mercury cups for a few moments disturbed the indications and rendered them useless for some time.

3184. In order to ascertain practically, *i. e.* experimentally, the comparative value of degrees in different parts of the scale or graduation of this instrument and so to render it a measurer, the following trials were made. A loop like that before described (3133.), fig. 2, was connected with the galvanometer by communications which removed the loop 9 feet from the instrument, and it was then fixed. A compound bar-magnet consisting of two plates, each 12 inches long, 1 inch broad, and 0·5 in thickness, was selected of such strength as to lift a bunch of clean iron filings, averaging 45 grains at either extremity. Blocks were arranged at the loop, so that this magnet, held in a vertical position, could have one end passed downwards through the loop until the latter coincided with the equator of the magnet (3191.); after which it could be quickly removed and the same operation be repeated at pleasure. When the magnet was thus moved, the loop being unconnected (at one of the mercury cups) with the galvanometer, there was no sensible change of place in the needles; the direct influence of the magnet at this distance of 9 feet being too small for such an effect.

Fig. 2.



3185. It must be well understood, that, in all the observations made with this instrument, the *swing* is observed and counted as the effect produced, unless otherwise expressed. A constant current in an instrument will give a constant and continued

deflection, but such is not the case here. The currents observed are for short periods, and they give, as it were, a blow or push to the needle, the effect of which, in swinging the needle, continues to increase the extent of the deflection long after the current is over. Nevertheless the extent of the swing is dependent on the electricity which passed in that brief current; and, as the experiments seem to indicate, is simply proportional to it, whether the electricity pass in a longer or a shorter time (3104.), and notwithstanding the comparative variability of the current in strength during the time of its continuance.

3186. The compound bar being introduced once into the loop and left there, the swing at the galvanometer was observed and found to be 16°; the galvanometer needle was then brought to zero, and the bar removed, which gave a reverse current and swing, and this also was 16°. Many alternations, as before described, gave 16° as the mean result, *i. e.* the result of one intersection of the lines of force of this magnet (3102.). In order to comprehend the manner in which the effect of two or more intersections of these lines of force were added together, it should be remembered that a swing of the needle from right to left occupied some time (13 seconds); so that one is able to introduce the magnet into the loop, then break the electric circuit by raising one end of the communicating wire out of the mercury, remove the magnet, which by this motion does nothing, restore the mercury contact, and reintroduce the magnet into the loop, before a tenth part of the time has passed, during which the needles, urged by the first impulse, would swing. In this way two impulses could be added together, and their joint effect on the needle observed; and, indeed, by practice, three and even four impulses could be given within the needful time, *i. e.* within one-half or two-thirds of the time of the full swing; but of course the latter impulses would have less power upon the needles, because these would be more or less oblique to the current in the copper coil at the time when the impulses were given. There can be no doubt, that, as regarded the currents induced in the loop by the magnet, they would be equal on every introduction of the same magnet.

3187. Proceeding in this way I obtained results for one, two, three, and even four introductions with the same magnet.

One introduction	15°
Two introductions	31·25
Three introductions	46·87
Four introductions	58·50

Here the approximation to 1, 2, 3, 4 cannot escape observation*; and I may remark,

* See note to (3189.) $\sin \frac{15}{2} = \sin 7^\circ 30' = {\cdot}130526$ $\quad {\cdot}130526$

$$\sin\frac{31{\cdot}25}{2} = \sin 15{\cdot}625 = \sin 15\ 37{\cdot}5 = {\cdot}269200 \qquad \frac{269200}{2} = {\cdot}134600$$

$$\sin\frac{46{\cdot}87}{2} = \sin 23{\cdot}435 = \sin 23\ 26{\cdot}1 = {\cdot}3976818 \qquad \frac{3976818}{3} = {\cdot}1328606$$

$$\sin\frac{58{\cdot}50}{2} = \sin 29{\cdot}25 = \sin 27\ 15 = {\cdot}4886212 \qquad \frac{4886212}{4} = {\cdot}1221553$$

that, whilst observing the place attained at the end of a swing which is retained only for an instant, some degree of error must creep in; and that that error must be greatest, in the first number, where it falls altogether upon the unit of comparison than in the other observations, where only one-half or one-third of it is added to a half or a third of the whole result. Thus, if we halve the arc for two introductions of the pole, it gives $15^\circ{\cdot}625$; if we take the third of that for three introductions, it gives $15^\circ{\cdot}61$;—numbers which are almost identical, so that if the first number was increased by only $0^\circ{\cdot}6$, the proportion would be as 1, 2 and 3. The reason why the fourth, which is $14^\circ{\cdot}625$, is less, may perhaps be referred to the cause already assigned, namely, the declination distance of the needle from the coil when that impulse was given (3186.).

3188. In order to avoid in some degree this case, and to compare the degrees at the beginning of the scale, which are most important for the comparison of future experiments with one another, I took one of the bars of the compound magnet employed above (3184.). The results were as follows:—

One introduction	$\overset{\circ}{8}$
Two introductions	15·75
Three introductions	23·87
Four introductions	31·66

which numbers are very closely as 1, 2, 3 and 4. If we divide as before, we have 8°, $7^\circ{\cdot}87$, $7^\circ{\cdot}95$, $7^\circ{\cdot}91$; so that if only 0·09 be subtracted from the first observation, or 8°, it leaves that simple result*.

3189. Hence it appears, that in this mode of applying and measuring the magnetic powers, the number of degrees of swing deflection are for small arcs nearly proportional to the magnetic force which has been brought into action on the moving wire†.

* $\sin\frac{8}{2} = \sin\overset{\circ}{4} = {\cdot}0697565 \qquad {\cdot}0697565$

$\sin\frac{15{\cdot}75}{2} = \sin 7{\cdot}875 = \sin 7^\circ\, 52'{\cdot}5 = {\cdot}1370123 \qquad \frac{1370123}{2} = {\cdot}0685061$

$\sin\frac{23{\cdot}87}{2} = \sin 11{\cdot}935 = \sin 11\ 56{\cdot}1 = {\cdot}2068019 \qquad \frac{2068019}{3} = {\cdot}0689340$

$\sin\frac{31{\cdot}66}{2} = \sin 15{\cdot}83 = \sin 15\ 49{\cdot}8 = {\cdot}2727840 \qquad \frac{2727840}{4} = {\cdot}0681960$

† Mr. Christie has recalled my attention to a paper in the Philosophical Transactions, 1833, p. 95, in which he has investigated, at p. 111, &c., the effect of what may be called magneto-electric impulses in deflecting the magnetic needle. He found that the velocity of the projection of the needle, which is a measure of the force acting upon it at the instant of its moving, will be proportional to the sine of half the arc of swing. My statement, therefore, would as a general expression be erroneous; but for small arcs the results as given by it are not far from the truth. The error does not interfere with the general reasoning and conclusions of the paper; and as the numbers are the results of experiment, which, though made with a first and therefore rough apparatus, were still made with some care, and are expressed simply as deflections, I prefer their appearance as they are rather than in an altered state. Mr. Christie has been so kind as to give me the true expression of force for many of the cases, and I have inserted the results as foot-notes where the cases occur.—Jan. 26, 1852.

3190. I have found the needles very constant in their strength for days and weeks together. By care, the constancy of their state for a day is easily secured, and that is all that is required in comparative experiments. Those which I have in use weigh with their axis and indicating wire 9 grains; and when out of the copper coil vibrate to and fro once in 26 seconds.

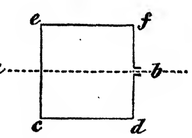
3191. With this instrument thus examined, I repeated most of the experiments with loops formerly described (3133. &c.), with the same results as before. It was also ascertained that the equator of a regular bar-magnet was the place at which the loop should be arrested, to produce the maximum action; and that if it came short of, or passed beyond that place, the final result was less. Employing a magnet 12 inches long, when the loop passed

2·3 inches over the pole the deflection was	5°·91
4·1 inches over the pole the deflection was	7·50
5·1 inches over the pole the deflection was	7·74
6·1 inches over the pole the deflection was	8·16
8·0 inches over the pole the deflection was	7·75
9·0 inches over the pole the deflection was	6·50

¶ ii. *Revolving Rectangles and Rings*.*

3192. The form of moving wire which I have adopted for experiments with the magnetic forces of the earth (3177.), is either that of a rectangle or a ring. If a wire rectangle (fig. 3) be placed in a plane, perpendicular to the dip and then turned once round the axis *a b*, the two parts *c d* and *e f* will twice intersect the lines of magnetic force within the area *c e d f*. In the first 180° of revolution the contrary direction in which the two parts *c d* and *e f* intersect those lines, will cause them to conspire in producing one current, tending to run round the rectangle (161) in a given direction; in the following 180° of revolution they will combine in their effect to produce a contrary current; so that if the first current is from *d* by *c e* and *f* to *d* again, the second will be from *d* by *f e* and *c* to *d*. If the rectangle, instead of being closed, be open at *b*, and the ends there produced be connected with a commutator, which changes sides when the rectangle comes into the plane perpendicular to the dip, *i. e.* at every half revolution, then these successive currents can be gathered up and sent on to the galvanometer to be measured. The parts *c e* and *d f* of the

Fig. 3.

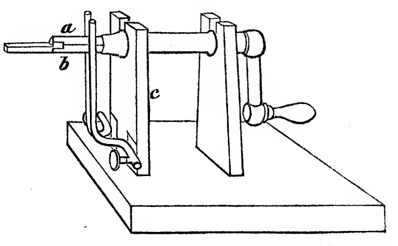


* A friend has pointed out to me that in July 1832, Nobili made experiments with rotating rings or spirals subject to the earth's magnetic influence; they were subsequent to and consequent upon my own experiments upon swinging wires (171, 148.) and revolving globes (160.) of January 1832; but he extended the considerations to the *thickness* of the wire; the *diameter* of the spirals and the *number* of the spirals dependent upon the *length* of the wire. The results (tabulated) will be found in vol. i. page 244, &c. of the Florence edition of his Mémoires.—March 1, 1852.

rectangle may be looked upon simply as conductors; for as they do not in their motion intersect any of the lines of force, so they do not tend to produce any current.

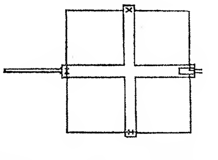
3193. The apparatus which carries these rectangles, and is also the commutator for changing the induced currents, consists of two uprights, fixed on a wooden stand, and carrying above a wooden horizontal axle, one end of which is furnished with a handle, whilst the other projects, and is shaped as in fig. 4. It may there be seen, that two semi-cylindrical plates of copper *a b* are fixed on the axle, forming a cylinder round it, except that they do not touch each other at their edges, which therefore leave two lines of separation on opposite sides of the axle. Two strong copper rods, 0·2 of an inch in diameter, are fixed to the lower part of the upright *c*, terminating there in sockets with screws for the purpose of receiving the ends of the rods proceeding from the galvanometer cups (3180.): in the other direction the rods rise up parallel to each other, and being perfectly straight, press strongly against the curved plates of the commutator on opposite sides: the consequence is, that, whenever in the rotation of the axle, the lines of separation between the commutator plates arrive at and pass the horizontal plane, their contact with these bearing rods is changed, and consequently the direction of the current proceeding from these plates to the rods, and so on to the galvanometer, is changed also. The other or outer ends of the commutator plates are tinned, for the purpose of being connected by soldering to the ends of any rectangle or ring which is to be subjected to experiment.

Fig. 4.



3194. The rectangle itself is tied on to a slight wooden cross (fig. 5), which has a socket on one arm that slides on to and over the part of the wooden axle projecting beyond the commutator plates, so that it shall revolve with the axle. A small copper rod forms a continuation of that part of the frame which occupies the place of axle, and the end of this rod enters into a hole in a separate upright, serving to support and steady the rectangle and its frame. The frames are of two or three sizes, so as to receive rectangles of 12 inches in the side, or even larger, up to 36 inches square. The rectangle is adjusted in its place, so that it shall be in the horizontal plane when the division between the commutator plates is in the same plane, and then its extremities are soldered to the two commutator plates, one to each. It is now evident, that when dealing with the lines of force of the earth, or any other lines, the axle has only to be turned until the upright copper rods touch on each side at the separation of the commutator plates, and then the instrument adjusted in position, so that the plane of the ring or rectangle is perpendicular to the direction of the lines of force which are to be examined, and then any revolution of the commutator and intersecting wire will produce the maximum current which such wire and such magnetic force can produce. The lines of terrestrial magnetic force are inclined at an angle

Fig. 5.



of 69° to the horizontal plane. As, however, only comparative results were required, the instrument was, in all the ensuing experiments, placed in the horizontal plane, with the axis of rotation perpendicular to the plane of the magnetic meridian; under which circumstances no cause of error or variation was introduced into the results. As no extra magnet was employed, the commutator was placed within 3 feet of the galvanometer, so that two pieces of copper wire 3 feet long and 0·2 of an inch in thickness, sufficed to complete the communication. One end of each of these dipped into the galvanometer mercury cups, the other ends were tinned, amalgamated, introduced into the sockets of the commutator rods (3193.), and secured by the pinching screw (fig. 4).

3195. When a given length of wire is to be disposed of in the form best suited to produce the maximum effect, then the circumstances to be considered are contrary for the case of a loop to be employed with a small magnet (39. 3184.), and a rectangle or other formed loop to be employed with the lines of terrestrial force. In the case of the small magnet, *all* the lines of force belonging to it are inclosed by the loop; and if the wire is so long that it can be formed into a loop of two or more convolutions, and yet pass over the pole, then twice or many times the electricity will be evolved that a single loop can produce (36.). In the case of the earth's force, the contrary result is true; for as in circles, squares, similar rectangles, &c. the areas inclosed are as the squares of the periphery, and the lines of force intersected are as the areas, it is much better to arrange a given wire in one simple circuit than in two or more convolutions. Twelve feet of wire in one square intersects in one revolution the lines of force passing through an area of nine square feet, whilst if arranged in a triple circuit, about a square of one foot area, it will only intersect the lines due to that area; and it is thrice as advantageous to intersect the lines within nine square feet once, as it is to intersect those of one square foot three times.

3196. A square was prepared, containing 4 feet in length of copper wire 0·05 of an inch in diameter; it inclosed one square foot of area, and was mounted on the commutator and connected in the manner already described (3194.). Six revolutions of it produced a swing deflection of 14° or 15°, and twelve quick revolutions were possible within the required time (3104.). The results of *quick* and *slow* revolutions were first compared. Six slow revolutions gave as the average of several experiments 15°·5 swing. Six moderate revolutions gave also an average of 15°·5; six quick revolutions gave an average of 15°·66. At another time twelve moderate revolutions gave an average of 28°·75, and twelve quick revolutions gave an average of 31°·33 swing. As before explained (3186.), the probable reason why the quick revolutions gave a larger result than the moderate or slow revolutions is, that in slow time the later revolutions are performed at a period when the needle is so far from parallel with the copper coil of the galvanometer, that the impulses due to them are less effectually exerted. Hence a small or moderate number of revolutions and a quick motion is

best. The difference in the extreme case is less than might have been expected, and shows that there is no practical objection in this respect to the method proposed of experimenting with the lines of magnetic force.

3197. In order to obtain for the present an expression of the power of the earth's magnetic force by this rectangle, observations were made on both sides of zero, as already recommended (3182.). Nine moderately quick direct revolutions (*i. e.* as the hands of the clock) gave as the average of many experiments 23°·87, and nine reverse revolutions gave 23°·37; the mean of these is 23°·62 for the nine revolutions of the rectangle, and therefore 2°·624 per revolution. Now the six quick revolutions (3196.) gave 15°·66, which is 2°·61 per revolution, and the twelve quick revolutions gave 31°·33, which is also 2°·61 per revolution; and these results of 2°·624, 2°·61, and 2°·61, are very much in accordance, and give great confidence in this method of investigating magnetic forces*.

3198. A rectangle was prepared of the same length (4 feet) of the same wire, but the sides were respectively 8 and 16 inches (fig. 6), so that when revolving the intersecting parts should be only 8 inches in length instead of 12. The area of the rectangle was necessarily 128 square inches instead of 144. This rectangle showed the same difference of quick and slow rotations as before (3196.).

Fig. 6.

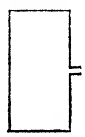
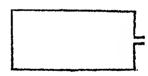


Fig. 7.



When nine direct revolutions were made, the result was 20°·87 swing. Nine reverse revolutions gave an average of 20°·25 swing; the mean is 20°·56, or 2°·284 per revolution. A third rectangle was prepared of the same length and kind of wire, the sides of which were respectively 8 and 16 inches long (fig. 7), but now so revolved that the intersecting parts were 16 inches, or twice as long as before; the area of the rectangle remained the same, *i. e.* 128 inches. The like effect of slow and quick revolutions appeared as in the former cases (3196. 3198.). Nine direct revolutions gave as the average effect 20°·75; and nine reverse revolutions produced 21°·375; the mean is 21°·06, or 2°·34 per revolution.

3199. Now 2°·34 is so near to 2°·284, that they may in the present state of the investigation be considered the same. The little difference that is evident, was, I suspect, occasioned by centrifugal power throwing out the middle of the longer intersecting parts during the revolution. The coincidence of the numbers shows, that the variation in the arrangement of the rectangle and in the length of the parts of the wires intersecting the lines of magnetic force, have had no influence in altering the result, which, being dependent alone on the number of lines of force intersected, is the same for both; for the area of the rectangles is the same. This is still further shown by comparing the results with those obtained with the square. The area in

* $\sin\frac{15\cdot66}{2}=\sin \overset{\circ}{7}\cdot83=\sin \overset{\circ}{7}\ \overset{\prime}{49}\cdot8=\cdot1362343 \qquad \frac{1362343}{6}=\cdot0227057$

$\sin\frac{23\cdot62}{2}=\sin 11\cdot81=\sin 11\ 48\cdot6=\cdot2047069 \qquad \frac{2047069}{9}=\cdot0227474$

$\sin\frac{31\cdot33}{2}=\sin 15\cdot665=\sin 15\ 40=\cdot2700403 \qquad \frac{2700403}{12}=\cdot0225034$

that case was 144 square inches, and the effect per revolution 2°·61. With the long rectangles the area is 128 square inches, and the mean of the two results is 2°·312 per revolution. Now 144 square inches is to 128 square inches as 2°·61 is to 2°·32; a result so near to 2°·312 that it may be here considered as the same; proving that the electric current induced is directly as the lines of magnetic force intersected by the moving wire*.

3200. It may also be perceived that no difference is produced when the lines of force are chiefly disposed in the direction of the motion of the wire, or else, chiefly in the direction of the length of the wire; *i. e.* no alterations are occasioned by variations in the *velocity* of the motion, or of the length of the wire, provided the amount of lines of magnetic force intersected remains the same.

3201. Having a square on the frame 12 inches in the side but consisting of copper wire 0·1 of an inch in thickness, I obtained the average result of many observations for one, two, three, four and five revolutions of the wire.

One revolution gave	7°	equal to	7°	per revolution.
Two revolutions gave	13·875	equal to	6·937	per revolution.
Three revolutions gave	21·075	equal to	7·025	per revolution.
Four revolutions gave	28·637	equal to	7·159	per revolution.
Five revolutions gave	37·637	equal to	7·527	per revolution.

These results are exceedingly close upon each other, especially for the first 30°, and confirm several of the conclusions before drawn (3189. 3199.) as to the indications of the instrument, the amount of the curves, &c.†

* Oblong rectangles of 128 square inches area give a mean of 20°·81 (3198.). The rectangle of 144 square inches gave a mean of 23°·62 (3197.).

$$\sin\frac{20{\cdot}81}{2}=\sin 10^\circ{\cdot}405=\sin 10^\circ\ 24'{\cdot}3=\cdot1806049$$

$$\sin\frac{23{\cdot}62}{2}=\sin 11{\cdot}81\ =\sin 11\ 48{\cdot}6=\cdot2047069$$

$$\frac{128}{144}=\frac{8}{9}\qquad \begin{array}{l}\cdot1806049\times9=1{\cdot}6254441\\ \cdot2047069\times8=1{\cdot}6376552\end{array}\qquad \text{Or thus: }\begin{array}{l}\dfrac{\cdot1806049}{8}=\cdot0225756\\[2ex] \dfrac{\cdot2047069}{9}=\cdot0227452\end{array}$$

†

$$\begin{array}{llll}
 & & \text{Differences.} & \\
\sin\frac{7}{2}=\sin\ 3^\circ{\cdot}30 & =\cdot0610485 & & \cdot0610485\\
 & & \cdot0597381 & \\
\sin\frac{13{\cdot}875}{2}=\sin\ 6{\cdot}9375=\sin\ 6^\circ\ 56'{\cdot}25 & =\cdot1207866 & & \frac{\cdot1207866}{2}=\cdot0603933\\
 & & \cdot0620924 & \\
\sin\frac{21{\cdot}075}{2}=\sin\ 10{\cdot}5375=\sin\ 10\ 32{\cdot}25 & =\cdot1828790 & & \frac{\cdot1828790}{3}=\cdot0609596\\
 & & \cdot0644329 & \\
\sin\frac{28{\cdot}637}{2}=\sin\ 14{\cdot}3185=\sin\ 14\ 19{\cdot}11 & =\cdot2473119 & & \frac{\cdot2473119}{4}=\cdot0618279\\
 & & \cdot0752595 & \\
\sin\frac{37{\cdot}637}{2}=\sin\ 18{\cdot}8185=\sin\ 18\ 49{\cdot}11 & =\cdot3225714 & & \frac{\cdot3225714}{5}=\cdot0645142
\end{array}$$

3202. At another time I compared the effect of equable revolutions with other revolutions very irregular in their rates, the motion being sometimes even backwards and continually differing in degree by fits and starts, yet always so that within the proper time a certain number of revolutions should have been completed. The rectangle was of wire 0·2 of an inch thick; the mean of many experiments, which were closely alike in their results, gave for two smooth, equable revolutions 17°·5, and also for two irregular uncertain revolutions the same amount of 17°·5.

3203. The relation of the current produced to the mass of the wire was then examined; a relation, which has been investigated on a former occasion by loops and small magnets (3133.)*. For the present purpose two other equal squares were prepared, each a foot in the side, but the copper wire of which they consisted was respectively 0·1 and 0·2 of an inch in diameter; so that with the former rectangle they formed a series of three, having the same size, shape and area, but the masses of the moving wire increasing in the proportion of one, four and sixteen. When the rectangle of 0·1 wire was employed, six direct revolutions gave an average result of 41°·75, and six to the left gave 46°·25; the mean of the two is 44°, and this divided by 6 gives 7°·33 as the deflection per revolution. Again, three direct revolutions gave 20°·12, and three reverse revolutions 23°·1; the mean being 21°·61, and the deflection per revolution 7°·20. This is very close to the former result with six revolutions, namely 7°·33, and is a large increase upon the effect of the rectangle of wire 0·05 in diameter, namely 2°·61; nevertheless, it is not as 4 : 1; nor could such a result be expected, inasmuch as the mass of the chief conductor remained the same (3137.). When the results are compared with those made with like wires in the form of loops, they are found to be exceedingly close; in that case the results were as 16° to 44°·4 (3136.), which would accord with a ratio in the present case of 2°·61 to 7°·26; and it is as 2°·61 to 7°·242, almost identical.

3204. The average of the direct and reverse revolutions is seen above to differ considerably, *i. e.* up to 4° and 5° in the higher case. This does not indicate any error in principle, but results simply from the circumstance, that when the needles were quiescent in the galvanometer, they stood a little on one side of zero (3182.). I did not wish to adjust the instrument at the time, as I was watching for spontaneous alterations of the zero place, and prefer giving the numbers as they came out in the graduation, to any pen-and-ink correction of the notes.

3205. The third square of 0·2 wire gave such large swings, that I employed only a small number of revolutions. Three direct revolutions gave an average of 25°·58; three reverse revolutions gave 28°·5; the mean is 27°·04, and the amount per revolution 9°·01. Again, two direct revolutions gave 17°·5; two reverse revolutions gave 18°; the mean is 17°·75, and the amount per revolution 8°·87; the mean of the two final

* See a corresponding investigation by Christie. Philosophical Transactions, 1833, p. 120.

results is 8°·94, and is again an increase on the effect produced by the preceding rectangle of wire, only half the diameter of the present. This thickness of wire was also employed formerly as a loop (3136.); and if we compare the results then obtained with the present results, it is remarkable how near they approach to each other; a circumstance which leads to great confidence in the principles and practice of both forms of examination. When wires having masses in the proportion of 1 : 4 and 16 were employed as loops, the currents indicated by the galvanometer were as 1·00, 2·77, and 3·58; now that they are employed as rectangles subject to the earth's magnetic power, they are as 1·00, 2·78, and 3·45*.

3206. I formed a square, 12 inches in the side, of four convolutions of copper wire 0·05 of an inch in diameter; the single wire which formed it was consequently 16 feet long. Such a rectangle will, in revolving, intersect the same number of lines of magnetic force as the former rectangle made with wire 0·1 in diameter (3203.); there will also be the same mass of wire intersecting the lines, but, as a conductor, the first wire has in respect of diameter, only one-fourth the conducting power of the second; and then, to increase the obstruction, it is four times as long. Six direct revolutions gave an average result of 20°·6, and six reverse revolutions 19°·7; the mean is 20°·15, and the proportion per revolution 3°·36. With the other rectangle having equal area and mass, but a single wire (3203.), the result per revolution was 7°·26; being above, though near upon twice as much as in the present case. Hence for such an excellent conducting galvanometer as that described (3123. 3178.), the moving wire had better be as one single thick wire rather than as many convolutions of a thin one. If it be, under all variations of circumstances, the same wire for the same area, then, of course, two or more convolutions are better than one.

3207. It was to be expected, however, that the thin wire rectangle would produce a current of more *intensity* than that in the thick wire, though less in quantity; and to prove this point experimentally, I connected the two rectangles in succession with Ruhmkorff's galvanometer (3086.), having wire only $\frac{1}{135}$th of an inch in diameter. That of the single thick wire now gave only 1°·66 of swing for twelve revolutions of the rectangle, or 0°·138 per revolution; whilst the other of four convolutions of thin

* $\sin\frac{27·04}{2} = \sin 13°·52 = \sin 13°\ 31'·2 = ·2337848$ $\quad \frac{·2337848}{2} = ·0779283$. The square 12 inches side, of wire 0·05 in diameter, gave for six revolutions (3196. 3197.) ·0227057 as $\sin\frac{1}{2}$ A for one revolution. A like square of wire 0·10 in diameter gave for five revolutions (3021.) $\frac{·3225714}{2} = ·06451428$ as $\sin\frac{1}{2}$ A for one revolution. A like square of wire 0·20 in diameter gave ·0779283 as $\sin\frac{1}{2}$ A for one revolution

$$\frac{·06451428}{·0227057} = 2·841. \qquad \frac{·0779283}{·0227057} = 3·432.$$

wire gave for twelve revolutions 7°·33, or 0°·61 per revolution. Now the needles of the two instruments were not very different in weight and other circumstances, so that without pretending to an accurate comparison, we may still perceive an immense falling-off in both cases, due to the obstruction of the fine wire in the RUHMKORFF's galvanometer; for the thick wire it is from 7°·26 to 0°·138, and for the thin wire from 3°·36 to 0°·610. Still the thin wire rectangle has lost far less proportionately in power than the other; and by this galvanometer is above four times greater in effect than the rectangle of thicker wire. Of the thick wire effect less than a *fiftieth* passes the fine wire galvanometer, all the rest is stopped; of the fine wire effect more than ten times this proportion, or between a fourth and a fifth (because of the higher intensity of the current), surmounts the obstruction presented by the instrument. The quantity of electricity which really passes through the fine wire galvanometer is of course far less than in the proportion indicated above. The thick wire coil makes at the utmost four convolutions about the needles, whereas in the fine wire coil there are probably four hundred or more; so that the electricity which really travels forward as a current, is probably not a hundredth part of that which would be required to give an equal deflection in the thick wire galvanometer. Such a circumstance does not disturb the considerations with respect to the relative intensity of the magneto-electric currents from the two rectangles, which have been stated above.

3208. A large square was now constructed of copper wire 0°·2 of an inch in diameter. The square was 36 inches in the side, and therefore consisted of 12 feet of wire, and inclosed an area of 9 square feet; it was attached to the commutator by expedients, which, though sufficient for the present, were not accurate in the adjustments. It produced a fine effect upon the thick wire galvanometer (3178.); for one revolution caused a swing deflection of 80° or more; and when its rotation was continuous the needles were permanently deflected 40° or 50°. It was very interesting to see how, when this rectangle commenced its motion from the horizontal plane, the current increased in its intensity and then diminished again, the needles showing, that whilst the first 10° or 20° of revolution were being passed, there was very little power exerted in them; but that when it was towards, or near the 90°, the power was great; the wires then intersecting the lines of force nearly at right angles, and therefore, with an equal velocity, crossing the greatest number in a given time. It was also very interesting, by the same indications, to see the two chief impulses (3192.) given in one revolution of the rectangle. Being large and massive in proportion to the former wires, more time was required for a rotation than before, and the point of *time* or *velocity* of rotation became more essential. One rotation in a second was as much as I could well produce. A speed somewhat less than this was easy, convenient and quick enough; it gave for a single revolution near 80°, whilst a revolution with one-half or one-third the velocity, or less, gave only 60°, 50°, or even smaller amounts of deflection.

3209. Observations were now made on the measurement of one rotation having an easy quick velocity. The average of fifteen observations to the right, which came very near to each other, was $78^{\circ}{\cdot}846$; the average of seventeen similar observations to the left was $78^{\circ}{\cdot}382$; and the mean of these results, or $78^{\circ}{\cdot}614$, I believe to be a good first expression for this rectangle. On measuring the distances across after this result, I found that in one direction, *i. e.* across between the intersecting portions of wire, it was rather less than 36 inches; having therefore corrected this error, I repeated the observations and obtained the result of $81^{\circ}{\cdot}44$. The difference of $2^{\circ}{\cdot}83$, I believe to be a true result of the alteration and increase of the area on making it more accurately 9 square feet; and it is to me an evidence of the sensibility and certainty of the instrument.

3210. As the two impulses upon the needles in one revolution (3208.) are here sensibly apart in time, and as the needle has as evidently and necessarily left its first place before the second impulse is impressed upon it, so, that second impulse cannot be so effectual as the first. I therefore observed the results with half a revolution, and obtained a mean of $41^{\circ}{\cdot}37$ for the effect. This number evidently belongs to the first of the two impulses of one revolution; and if we subtract it from $81^{\circ}{\cdot}44$, it gives $40^{\circ}{\cdot}07$ as the value of the second impulse under the changed place of the needle. This difference of the two impulses of one revolution, namely $41^{\circ}{\cdot}37$ and $40^{\circ}{\cdot}07$, is in perfect accordance with the results that were to be expected.

3211. The square of this same copper wire, 0·2 in thickness, employed on a former occasion (3205.), had an area of one square foot, so that then the lines of force affected or affecting the moving wire, were one-ninth part of what they are in the present case: the effect then was $8^{\circ}{\cdot}94$ per revolution. If, in comparing these cases, we take the ninth part of $81^{\circ}{\cdot}44$, it gives $9^{\circ}{\cdot}04$; a number so near the former, that we may consider the two rectangles as proving the same result, and at the same time the truth of the statement, that the magneto-electric current evolved is as the amount of lines of force intersected. A ninth part of the result with the large rectangle ($78^{\circ}{\cdot}614$), before its area was corrected, is $8^{\circ}{\cdot}734$; so that the one is above and the other below the amount of the 12-inch rectangle. As that was not very carefully adjusted, nor indeed any of the arrangements made as yet with extreme accuracy, I have little doubt that with accurately adjusted rectangles the results would be strictly proportional to the areas*.

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* The 9 square feet rectangle gave $81^{\circ}{\cdot}44 \sin \frac{81{\cdot}44}{2} = \sin 40{\cdot}72 = \sin 40^{\circ}\, 43'{\cdot}2 = {\cdot}6523630$: or taking $41^{\circ}{\cdot}37$ for the half revolution for $\frac{1}{2}$ A (3210.) $\sin 41^{\circ}{\cdot}37 = \sin 41^{\circ}\, 22'{\cdot}2 = {\cdot}6609190$, which divided by nine give ·073435 as the force per square foot. The 1 square foot rectangle of like wire (3205.) gave ·07714, or ·07793 as the force of one revolution; the first of which is ·00370 more than $\frac{1}{9}$ of the measure of the effect of the large square; the difference being about $\frac{1}{29}$ of ·07714, or the whole force of one revolution.

3212. The moving wire, in place of being formed into a rectangle, may be adjusted as a ring; and then the advantage is obtained of the largest area which a given length of wire can inclose, and therefore for a uniform wire, the obstruction to the induced current, as respects its conduction, is the least. Small rings of one or several convolutions will probably be very valuable in the examination of small and local magnets under different circumstances. One consisting of ten spirals of copper wire 0°·032 of an inch in diameter, containing 49 inches, in a ring about 1·5 inch in diameter, gave but small results under the earth's influence; but when brought near a horseshoe magnet told, in its effects for every difference in distance or in position. A single ring 4 inches in diameter, being made of a convolution of copper wire 0·2 in thickness, was employed with the earth's magnetic force as before; it gave as the average of six revolutions many times repeated 5°·995, or 0°·999 per revolution. For twelve revolutions it gave a mean of 12°·375, or 1°·031 per revolution*; the mean of the two results with such different numbers of revolutions being 1°. Another ring, consisting of twenty-six convolutions of copper wire 0·04 of an inch in diameter, was constructed and had a mean diameter of 3·6 or 3·7 inches; it contained 300 inches in length of wire. So the masses of the metal in the two rings are nearly the same, but the latter wire is singly only $\frac{1}{25}$th of the mass of the former. It gave for twelve revolutions a mean of 6°·25, or 0°·52 per revolution. With the earth's power and the thick wire galvanometer, it gave therefore little more than half the result of the single thick wire ring. We know from former considerations (3206.), that if the 300 inches had been made into one single ring, it would have given a very high effect compared to the present.

3213. The application of the principle of the moving wire in the form of a revolving rectangle, makes the investigation of *conducting* power, and the results produced by difference in the nature of the *substance*, or in diameter, *i. e. mass*, or in *length*, very easy; and the obstruction offered by those parts, which moving not across but parallel to the lines of force (3071.), have no exciting action but perform the part of conductors merely, might be greatly removed by making them massive. They might be made to shift upon the axle so as to bear adjustment for different lengths of wires, and the commutator might in fact be made to a large extent a general instrument.

3214. In looking forward to further applications of the principle of the moving wire, it does not seem at all unlikely that by increased delicacy and perfection of the instrument, by increased velocity, by continued motion for a time in one direction and then reversal of the revolution with the reversal of the direction of the swing, &c., it may be applied with advantage hereafter to the investigation of the earth's magnetic force in different latitudes and places. To obtain the maximum

* $\sin \frac{5\cdot995}{2} = \sin \overset{\circ}{2}\cdot9975 = \sin \overset{\circ}{2}\ \overset{\prime}{59}\cdot85 =$ $\cdot0522925$

$\sin \frac{12\cdot375}{2} = \sin 6\cdot1875 = \sin 6\ \ 11\cdot25 = \cdot1077825$ $\frac{\cdot1077825}{2} = \cdot0538912.$

effect, the axis of rotation must be perpendicular to the lines of force, *i. e.* the dip. It would even be possible to search for the *direction* of the lines of force, or the dip, by making the axis of rotation variable about the line of dip, adjusting it in two directions until there was no action at the galvanometer, and then observing the position of the axis; a double commutator would be required corresponding to the lines of adjustment, but that is of very simple construction.

§ 36. *On the amount and general disposition of the Forces of a Magnet when associated with other magnets.*

3215. Prior to further progress in the experimental development by a moving wire of the disposition of the lines of magnetic force pertaining to a magnet, or of the physical nature of this power and its possible mode of action at a distance, it became quite essential to know what change, if any, took place in the amount of force possessed by a perfect magnet, when subjected to other magnets in favourable or adverse positions; and how the forces combined together, or were disposed of, *i. e.* generally, and in relation to the principle already asserted and I think proved, that the power is in every case definite under those different conditions. The representation of the magnetic power by *lines of force* (3074.), and the employment of the moving wire as a test of the force (3076.), will I think assist much in this investigation.

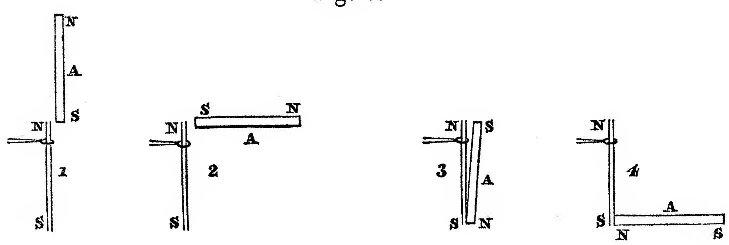
3216. For such a purpose an ordinary magnet is a very irregular and imperfect source of power. It not only, when magnetized to a given degree, is apt by slight circumstances to have its magnetic power diminished or exalted, in a manner which may be considered for the time, permanent; but if placed in adverse or favourable relations to other magnets, frequently admits of a considerable temporary diminution or increase of its power externally, which change disappears as soon as it is removed from the neighbourhood of the dominant magnet. These changes produce corresponding effects upon the moving wire, and they render any magnet subject to them unfit for investigation in relation to definite power. Unchangeable magnets are, therefore, required, and these are best obtained, as is well known, by selecting good steel for the bars, and then making them exceedingly hard; I therefore procured some plates of thin steel 12 inches long and 1 inch broad, and making them as hard as I could, afterwards magnetized them very carefully and regularly, by two powerful steel bar-magnets, shook them together in different and adverse positions for a little while, and then examined the direction of the forces by iron filings. Small cracks and irregularities were in this way detected in several of them; but two which were very regular in the disposition of their forces were selected for further experiment, and may be distinguished as the subjected magnets D and E.

3217. These two magnets were examined by the moving loop precisely in the manner before described (3133.), *i. e.* by passing the loop over one of the poles, observing the swing, removing it, and again observing the swing and taking an average of many results; the process was performed over both poles at different times. The loop

contained 7·25 inches in length of copper wire 0·1 of an inch in diameter, and was of course employed in all the following comparative experiments; the distance of the loop and magnets from the galvanometer was 9 feet. For one passage over the pole either on or off, *i. e.* for one intersection of the lines of force of the magnet D, the galvanometer deflection was 8°·36. For one intersection of the lines of force of the other bar E, the deflection was 8°·78. The two bars were then placed side by side with like poles together, and afterwards used as one magnet; their conjoined power was 16°·3, being only 0°·84 less than the sum of the powers of the two when estimated separately. This indicates that the component magnets do affect, and in this position reduce, each other somewhat; but it also shows how small the effect is as compared with ordinary magnets (3222.).

3218. The compound magnet D E (3217.) was now subjected to the close action of another magnet, sometimes under adverse, and at other times under favourable conditions; and was examined by the loop as to the sum of its power (not the direction) under these circumstances. For this purpose it was fixed, and another magnet A brought near, and at times in contact with it, in the positions indicated by the figure 8; the loop in each case being applied many times to D E, that a correct average of its power might be procured. The dominant magnet A was much the stronger of the two, having the power indicated by a swing deflection of 25°·74.

Fig. 8.



3219. When the relative position of the magnets was as at 1, then the power of D E was 16°·37; when as at 2, the power was 16°·4; when as at 3, it was 18°·75; and when as at 4, it was 17°·18. All these positions are such as would tend to raise, by induction, the power of the magnet D E, and they do raise it above its first value, which was 16°·3; but it is seen at once how little the first and second positions elevate it; and even the third, which presents the most favourable conditions, only increases the power 2°·45, which falls again in the fourth position.

3220. Then the dominant magnet A was placed in the same positions, but with the ends reversed, so as to exert an adverse or depressing influence; and now the results with D E were as follows:—

Position 1	15°·37
Position 2	15·68
Position 3	15·37
Position 4	16·06

All these are a little below the original force of D E, or 16°·3, as they ought to be, and show how slightly this hard bar-magnet is affected.

3221. A soft iron bar, now applied in the first, second and third positions instead of the magnet A, raised D E to the following values respectively, 16°·24, 16°·43, and 18°.

3222. When an ordinary bar-magnet was employed instead of the hard magnet D E, great changes took place. Thus a bar B, corresponding to bar A in size and general character, was employed in place of the hard magnet. Alone, B had a power of 14°·83, but when associated adversely with A, as in position 3 (3218.), its power fell to 7°·87, being reduced nearly one-half. This loss was chiefly due to a coercion internally, and not to a permanent destruction of the state of magnet B; for when A was removed, B rose again to 13°·06. When B was laid for a few moments favourably on A and then removed, it was found that the latter had been raised to a permanent external action of 15°·25.

3223. A very hard steel bar 6 inches long, 0·5 broad and 0·1 in thickness, given to me by Dr. Scoresby, was magnetized and then found, by the use of the loop, to have a value at my galvanometer of 6°·88 (3189.). It was submitted in position 2 to a compound bar-magnet like D E, having a power of 11°·73, or almost twice its own force, but whether in the adverse or the favourable position, its power was not sensibly altered. When submitted in like manner to a 12-inch bar-magnet having a force of 40°·21, it was raised to 7°·53, or lowered to 5°·87, but here the dominant magnet had nearly six times the power of the one affected.

3224. The variability of soft steel magnets, both in respect of their *absolute* degree of excitation or charge, and also of the disposition of the force externally and internally, when their degree of excitation may for the time be considered as the same, is made very manifest by this mode of examination; and the results agree well with our former knowledge in this respect. It is equally manifest, that hard and invariable magnets are requisite for a correct and close investigation of the disposition and characters of the magnetic force. A common soft bar-magnet may be considered as an assemblage of hard and soft parts, disposed in a manner utterly uncertain; of which some parts take a much higher charge than others, and change less under the influence of external magnets; whilst, because of the presence of other parts within, acting as the keeper or submagnet, they may seem to undergo far greater changes than they really do. Hence the value of these hard and comparatively unchangeable magnets which Scoresby describes.

3225. From these and such results, it appears to me, that with perfect, unchangeable magnets, and using the term *line of force* as a mere representant of the force as before defined (3071. 3072.), the following useful conclusions may be drawn.

3226. Lines of force of different magnets in favourable positions to each other coalesce.

3227. There is no increase of the total force of the lines by this coalescence; the section between the two associated poles gives the same sum of power as that of the section of the lines of the invariable magnet when it is alone (3217.). Under these

circumstances there is, I think, no doubt that the external and internal forces of the same magnet have the same relation and are equivalent to each other, as was determined in a former part of these Researches (3117.); and that therefore the equatorial section, which represents the sum of forces or lines of forces passing through the magnet, remains also unchanged (3232.).

3228. In this case the analogy with two or more voltaic batteries associated end to end in one circuit is perfect. Probably some effect, correspondent to *intensity* in the case of the batteries, will be found to exist amongst the magnets.

3229. The increase of power upon a magnetic needle, or piece of soft iron placed between two opposite, favourable poles, is caused by concentration upon it of the lines which before were diffused, and not by the addition of the power represented by the lines of force of one pole to that of the lines of force of the other. There is no more power represented by all the lines of force than before; and a line of force is not more powerful because it coalesces with a line of force of another magnet. In this respect the analogy with the voltaic pile is also perfect.

3230. A line of magnetic force being considered as a closed circuit (3117.), passes in its course through *both* the magnets, which are for the time placed so as to act on each other favourably, *i. e.* whose lines coincide and coalesce. Coalescence is not the addition of one line of force to another *in power*, but their union in one common circuit.

3231. A line of force may pass through many magnets before its circuit is complete; and these many magnets coincide as a case with that of a single magnet. If a thin bar-magnet 12 inches long be examined by filings (3235.), it will be found to present the well-known beautiful system of forces, perfectly simple in its arrangement. If it be broken in half, without being separated, and again examined, the manner in which, from the destruction of the continuity, the transmission of the force at the equator is interfered with, and many of the lines, which before were within are made to appear externally there, is at once evident, Plate IX. fig. 6. Of those lines, which thus become external, some return back to the pole which is nearest to the new place, at which the lines issue into the air, making their circuit through only one of the halves of the magnet; whilst others proceed onward by paths more or less curved into the second half of the magnet, keeping generally the direction or polarity which they had whilst within the magnet, and complete their circuit through the two. Gradually separating the two halves, and continuing to examine the course of the lines of force, it is beautiful to observe how more and more of the lines which issue from the two new terminations, turn back to the original extremities of the bar, fig. 7, and how the portion which makes a common circuit through the two halves diminishes, until the halves are entirely removed from each other's influence, and then become two separate and independent magnets. The same process may be repeated until there are many magnets in place of one.

3232. All this time the amount of lines of force is the same if the fragments of the

bar preserve their full state of magnetism ; *i. e.* the sum of lines of force in the equator of *either* of the new magnets is equal to the sum of lines of force in the equator of the original unbroken bar. I took a steel bar 12 inches long, 1 inch broad and 0·05 of an inch thick, made it very hard, and magnetized it to saturation by the use of soft iron cores and a helix; its power was 6°·9. I broke it into two pieces nearly in the middle, and found the power of these respectively 5°·94 and 5°·89; indicating a fall not more than was to be expected considering the saturated state of the original magnet. When these halves were placed side by side, with like poles together as a compound magnet, they had a joint power of 11°·06, which, though it shows a mutual quelling influence, is not much below the sum of their powers ascertained separately. All this is in perfect harmony with the voltaic battery, where lines of dynamic electric force are concerned. If, as is well known, we separate a battery of 20 pair of plates into two batteries of 10 pair, or 4 batteries of 5 pair, each of the smaller batteries can supply as much dynamic electricity as the original battery, provided no sensible obstruction be thrown into the course of the lines, *i. e.* the path of the current.

3233. When magnets are placed in an adverse position, as neither could add power to the other in the former case, so now each retains its own power; and the lines of magnetic force represent this condition accurately. Two magnets placed end to end with like poles together are in this relation; so also are they if placed with like poles together side by side. In the latter case the two acting as one compound magnet, give a system of lines of force equal to the sum of the two separately (3232.), minus the portion which, as in imperfect magnets, is either directed inwards by the softer parts or ceases to be excited altogether.

§ 37. *Delineation of Lines of Magnetic Force by iron filings.*

3234. It would be a voluntary and unnecessary abandonment of most valuable aid, if an experimentalist, who chooses to consider magnetic power as represented by lines of magnetic force, were to deny himself the use of iron filings. By their employment he may make many conditions of the power, even in complicated cases, visible to the eye at once; may trace the varying direction of the lines of force and determine the relative polarity; may observe in which direction the power is increasing or diminishing; and in complex systems may determine the neutral points or places where there is neither polarity nor power, even when they occur in the midst of powerful magnets. By their use probable results may be seen at once, and many a valuable suggestion gained for future leading experiments.

3235. Nothing is simpler than to lay a magnet upon a table, place a flat piece of paper over it, and then, sprinkling iron filings on the paper, to observe the forms they assume. Nevertheless, to obtain the best and most generally useful results, a few particular instructions may be desirable. The table on which the magnet is laid should be quite horizontal and steady. Means should be taken, by the use of thin boards or laths, or otherwise, to block up round the magnet, so that the paper which

is laid over it should be level. The paper should be without any cockle or bend, and perfectly flat, that the filings may be free to assume the position which the magnet tends to give them. I have found well-made cartridge or thin drawing-paper good for the purpose. It should not be too smooth in ordinary cases, or the filings, when slightly agitated, move too freely towards the magnet. With very weak or distant magnets I have found silvered paper sometimes useful. The filings should be clean, *i. e.* free from much dirt or oxide; the latter forms the lines but does not give good delineations. The filings should be distributed over the paper by means of a sieve more or less fine, their quantity being partly a matter of taste. It is to be remembered, however, that the filings disturb in some degree the conditions of the magnetic power where they are present, and that in the case of small magnets, as needles, a large proportion of them should be avoided. Large and also fine filings are equally useful in turn, when the object is to preserve the forms obtained. For the distribution of the latter it is better to use a fine sieve with the ordinary filings than to separate the filings first: a better distribution on the paper is obtained. The filings being sifted evenly on the paper, the latter should be tapped very lightly by a small piece of wood, as a pen-holder; the taps being applied wherever the particles are not sufficiently arranged. The taps must be perpendicularly downwards, not obliquely, so that the particles, whilst they have the liberty of motion, for an instant are not driven out of their places, and the paper should be held down firmly at one corner, so as not to shift right or left; the lines are instantly formed, especially with fine filings.

3236. The designs thus obtained may be fixed in the following manner, and then form very valuable records of the disposition of the forces in any given case. By turning up two corners of the paper on which the filings rest, they may be used as handles to raise the paper upwards from the magnet, to be deposited on a flat board or other plane surface. A solution of one part of gum in three or four of water having been prepared, a coat of this is to be applied equably by a broad camel-hair pencil, to a piece of cartridge paper, so as to make it fairly wet, but not to float it, and after wafting it through the air once or twice to break the bubbles, it is to be laid carefully over the filings, then covered with ten or twelve folds of equable soft paper, a board placed over the paper, and a half-hundred weight on the board for thirty or forty seconds. Or else, and for large designs it is a better process, whilst the papers are held so that they shall not shift on each other, the hand should be applied so as to rub with moderate pressure over all the surface equably and in one direction. If, after that, the paper be taken up, all the filings will be found to adhere to it with very little injury to the forms of the lines delineated; and when dry they are firmly fixed. If a little solution of the red ferroprussiate of potassa and a small proportion of tartaric acid be added to the gum-water, a yellow tint is given to the paper, which is not unpleasant; but besides that, prussian blue is formed under every particle of iron; and then when the filings are purposely or otherwise dis-

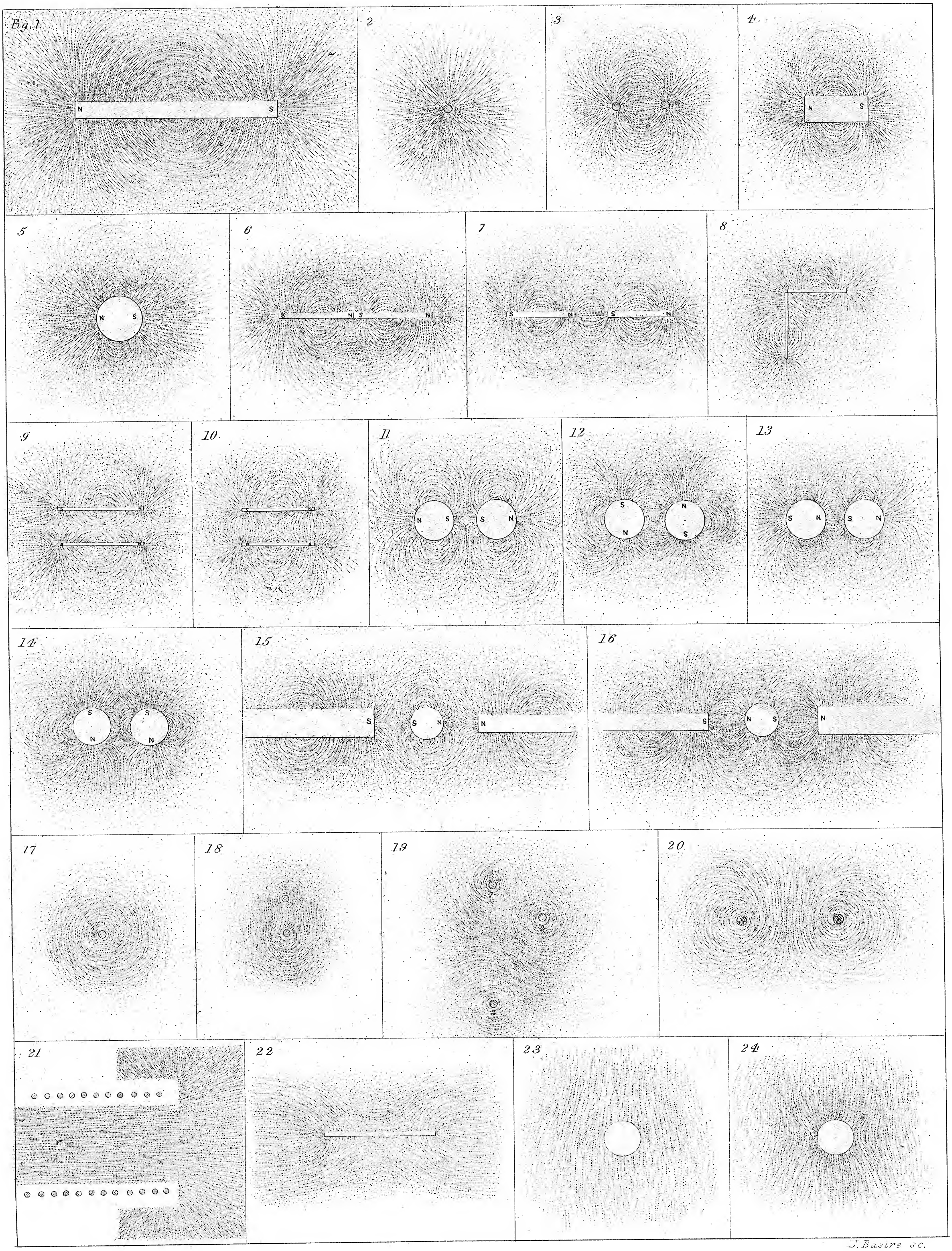
placed, the design still remains recorded. When the designs are to be preserved in blue only, the gum may be dispensed with and the red ferroprussiate solution only be used.

3237. It must be well understood that these forms give no indication by their appearance of the relative strength of the magnetic force at different places, inasmuch as the appearance of the lines depends greatly upon the quantity of filings and the amount of tapping; but the direction and forms of the lines are well given, and these indicate, in a considerable degree, the direction in which the forces increase and diminish.

3238. Plate IX. fig. 1, shows the forms assumed about a bar-magnet. On using a little electro-magnet and varying the strength of the current passed through it, I could not find that a variation in the strength of the magnet produced any alteration in the forms of the lines of force external to it. Fig. 2 shows the lines over a pole, and fig. 3 those between contrary poles. The latter accord with the magnetic curves, as determined and described by Dr. ROGET and others, with the assumption of the poles as centres of force. The difference between them and those belonging to a continuous magnet, shown in fig. 1, is evident. Figs. 4, 5 show the lines produced by short magnets. In the latter case the magnet was a steel disc about one inch in diameter and 0·05 in thickness. Fig. 6 shows the result when a bar-magnet is broken in half, but not separated. Fig. 7 shows the development of the lines externally at the two new ends as the halves are more and more separated (3231.). Figs. 8, 9 and 10 present the results, with the two halves or new magnets in different positions. Figs. 11, 12, 13 and 14 show the results with disc magnets. Fig. 15 shows the condition of a system of magnetic forces when it is inclosed by a larger one, and is contrary to it. Fig. 16 shows the coalescence of the lines of force (3226.) when the magnets are so placed that the polarities are in accordance.

3239. Fig. 17 exhibits the lines of force round a vertical wire carrying a current of electricity. Whether the wire was thick or thin appeared to make no difference as to the intensity of the forces, the current remaining the same. Fig. 18 represents the lines round two like currents when within mutual influence. Fig. 19 shows the result when a third current is introduced in the contrary direction. Fig. 20 presents the transition to a helix of three convolutions. Fig. 21 indicates the direction of the lines within and outside the end of a cylindrical helix, on a plane through its axis. Fig. 22 presents the effect when a very small soft iron core is within the helix.

3240. Figs. 23 and 24 give an experimental illustration of the principles which I have adopted in relation to atmospheric magnetism and the general cause of the daily variations, &c. (2864. 2917.). A hemisphere of pure nickel presented to me by Dr. PERCY, was supported with its flat face uppermost, and a large ring arranged round it to carry paper, which, resting both on the ring and the nickel, could then have iron filings sprinkled and arranged in form on it. The end of a bar-magnet in the same horizontal plane was adjusted about 2 inches from the nickel, and thus the



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forms of the lines of force associated with this pole could be determined over the place of the nickel hemisphere, under different circumstances, or even when it was removed. When the nickel was away, the forms of the lines of force were as in fig. 23; when the nickel was there, they were as in fig. 24. The application of a spirit-lamp to the nickel when in its place, raised its temperature to such a degree (above 600° FAHR.) that it lost its ordinary magnetic condition; and then the forms of the lines of force, as shown by filings, were the same as if the nickel was away. Removing the lamp, I was able to obtain the disposition of filings on successive pieces of paper, and as many as four results, like fig. 23, could be procured before the temperature had sunk so much as to cause the production of lines of force corresponding to fig. 24.

3241. These are exactly the same results with nickel as those I have assumed for the oxygen of the atmosphere. The change in the forms of the lines about the cooling nickel in this experiment are the same changes as those I have figured in the type globe of cooling air (2865. 2874.). Both nickel and oxygen are paramagnetic bodies, and change in the *same direction* by heating and cooling; and as the period of change with oxygen extends through degrees above and below common temperature (2861.), so inflections of the lines of force passing through the atmosphere, correspondent to those of the heating and cooling nickel, *must* take place to some extent. It is seen in the nickel results, that lines of force entirely outside of it do not for that reason continue an undeviating course, but are curved to and fro in consequence of the disposition of other lines within the nickel; a result, which, without reference to either one view or another of the physical action of the magnetic force, must be as true in the oxygen case as in the nickel case, because of the definite character of the magnetic force, whether represented by centres of action or by lines of power.

3242. Whether the amount of the deflection in the case of the atmosphere corresponds with the facts registered by observers, is a question which cannot be answered, I suppose, until we know the effect of very low temperatures upon the magnetic force of the atmosphere. In the nickel experiment the deflection is in places 30° or 40°; in nature the effect to be accounted for is not more than 13 or 14 minutes.

Royal Institution,
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